Lightest Neutralino in Extensions of the MSSM

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mainly based on preliminary work with

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Extended-MSSM Models

Extended MSSM models that solve the μ-problem

SUSY-conserving $\mu \approx \mathcal{O}$(EW/TeV) $\approx$ SUSY-breaking soft terms.

The MSSM does not provide the answer. [Kim, Nilles (1984)]

Look for extensions of the MSSM with a new symmetry that prevents original μ and generates effective μ with a Higgs singlet (a la NMSSM).

$$W_{\mathrm{MSSM}} = \mu H_1 H_2$$

$$W_{\mathrm{extended-MSSM}} = h_s S H_1 H_2 \longrightarrow \mu_{\mathrm{eff}} H_1 H_2$$

$$\mu_{\mathrm{eff}} = h_s \langle S \rangle \sim \mathcal{O}(\text{EW/TeV})$$

(after S gets EW/TeV scale VEV $\langle S \rangle \equiv \frac{s}{\sqrt{2}}$)

Using discrete symmetry, $\mathbb{Z}_i$

Discrete symmetries predict domain walls.

- Next-to-Minimal SSM (NMSSM)

$$W_{\mathrm{NMSSM}} = h_s S H_1 H_2 + \frac{\kappa}{3} S^3$$

($\mathbb{Z}_3$; domain walls $\longrightarrow$ large CMB anisotropy)

- Minimal Non-minimal SSM (MNSSM) / nearly Minimal SSM (nMSSM)

[Panagiotakopoulos, Tamvakis, Pilaftsis, Dedes, Hugonie, Moretti (1999 $\sim$ 2001)]

$$W_{\mathrm{nMSSM}} = h_s S H_1 H_2 + \alpha S$$

($\mathbb{Z}_5^R$/$\mathbb{Z}_7^R$; $6/7$-loop-generated tadpole term (αS) in Supergravity breaks a discrete symmetry and avoids gauge destabilization)

Using Abelian gauge symmetry, $U(1)'$

Gauge symmetries predict extra gauge bosons.

- $U(1)'$-extended Minimal SSM (UMSSM)

  $$W_{\rm UMSSM} = h_s S H_1 H_2$$

  (no domain wall; additional EW/TeV-scale gauge boson Z')

- $U(1)'$-extended SSM with multiple Singlets (multi-S)

  [Erler, Langacker, Li (2002)]

  $$W_{\rm multi-S} = h_s S H_1 H_2 + \lambda_s S_1 S_2 S_3$$

  (a variant; additional contribution to $M_{Z'}$ from more singlets)

$U(1)'$ may need (model-dependent) exotic fermions to cancel anomaly.

We assume they are heavy enough to give only insignificant effect.

Higgses and Neutralinos in extended-MSSM models

Model	Symmetry	Higgses	Neutralinos
MSSM	–	$H_1^0, H_2^0, A^0, H^\pm$	$\tilde{B}, \tilde{W}_3, \tilde{H}_1^0, \tilde{H}_2^0$
NMSSM	$\mathbb{Z}_3$	+ H_3^0, A_2^0	+ $\tilde{S}$
nMSSM	$\mathbb{Z}_5^R, \mathbb{Z}_7^R$	+ H_3^0, A_2^0	+ $\tilde{S}$
UMSSM	$U(1)'$	+ H_3^0	+ $\tilde{S}, \tilde{Z}'$
multi-S	$U(1)'$	+ $H_3^0, H_4^0, H_5^0, H_6^0, A_2^0, A_3^0, A_4^0$	+ $\tilde{S}, \tilde{S}_1, \tilde{S}_2, \tilde{S}_3, \tilde{Z}'$

The lightest neutralino (χ_1^0) property may change in extended-MSSM models (from well-known MSSM predictions) due to new additions (Higgsinos and gauginos) and interaction.

Neutralino mass matrix

- UMSSM : 6×6 matrix, in the basis of $\{\tilde{B}, \tilde{W}_3, \tilde{H}_1^0, \tilde{H}_2^0, \tilde{S}, \tilde{Z}'\}$

$$\begin{pmatrix} M_1 & 0 & -g_1 v_1/2 & g_1 v_2/2 & 0 & 0 \\ 0 & M_2 & g_2 v_1/2 & -g_2 v_2/2 & 0 & 0 \\ -g_1 v_1/2 & g_2 v_1/2 & 0 & -\mu_{\rm eff} & -\mu_{\rm eff} v_2/s & g_{Z'} Q'_{H_1} v_1 \\ g_1 v_2/2 & -g_2 v_2/2 & -\mu_{\rm eff} & 0 & -\mu_{\rm eff} v_1/s & g_{Z'} Q'_{H_2} v_2 \\ 0 & 0 & -\mu_{\rm eff} v_2/s & -\mu_{\rm eff} v_1/s & 0 & g_{Z'} Q'_S s \\ 0 & 0 & g_{Z'} Q'_{H_1} v_1 & g_{Z'} Q'_{H_2} v_2 & g_{Z'} Q'_S s & M_{1'} \end{pmatrix}$$

- nMSSM : First 5×5 submatrix
- NMSSM : First 5×5 submatrix with $\sqrt{2}\kappa s$ at $(5,5)$
- MSSM : First 4×4 submatrix
- multi-S : 9×9 matrix (3 more columns/rows from $\tilde{S}_{1,2,3}$)

  but, most realistic features at large $\tilde{S}_{1,2,3}, M_{1'}$ limit (nMSSM limit)

Direct constraints on the lightest neutralino (χ_1^0)

Constraints

- $\Gamma_Z^{\text{exp}} - \Gamma_Z^{\text{SM}} = (-2.0 \pm 2.6)$ MeV (LEP invisible Z width)
- $M_{\chi_1^\pm} > 104$ GeV (LEP bound on chargino mass)
- $0.1 \leq h_s \leq 0.75$ (naturalness & perturbativity)
- $\sqrt{h_s^2 + \kappa^2} \leq 0.75$ and $\kappa \geq 0.1$ for NMSSM ($\kappa \longrightarrow 0$ limit = nMSSM)
- $m_{h^0} > 114$ GeV (LEP bound on Higgs mass) does not apply to extended-MSSM models (where physical Higgs is a mixture of doublets and singlets).

Mass range of χ_1^0 allowed by direct constraints

We scan μ, $M_2 = 50 \sim 500$ GeV, $s = 50 \sim 2000$ GeV and apply the direct constraints.

Model	$M_{\chi_1^0}^{\min}$	dominant	cutoff	$M_{\chi_1^0}^{\mathrm{Max}}$	dominant	cutoff
MSSM	53 GeV	$\tilde{B}$	$M_{\chi_1^\pm} > 104$	248 GeV	$\tilde{B}$	$M_1 < 250$
NMSSM	16 GeV	$\tilde{S}$	$M_{\chi_1^\pm} > 104$	248 GeV	$\tilde{B}$	$M_1 < 250$
nMSSM	0 GeV	$\tilde{S}$		83 GeV	$\tilde{S}$	$h_s \leq 0.75$
UMSSM	0 GeV	$\tilde{S}$		248 GeV	$\tilde{B}$	$M_1 < 250$

Gaugino mass unification of $0.5M_2 \simeq M_1 = M_{1'}$ is assumed.

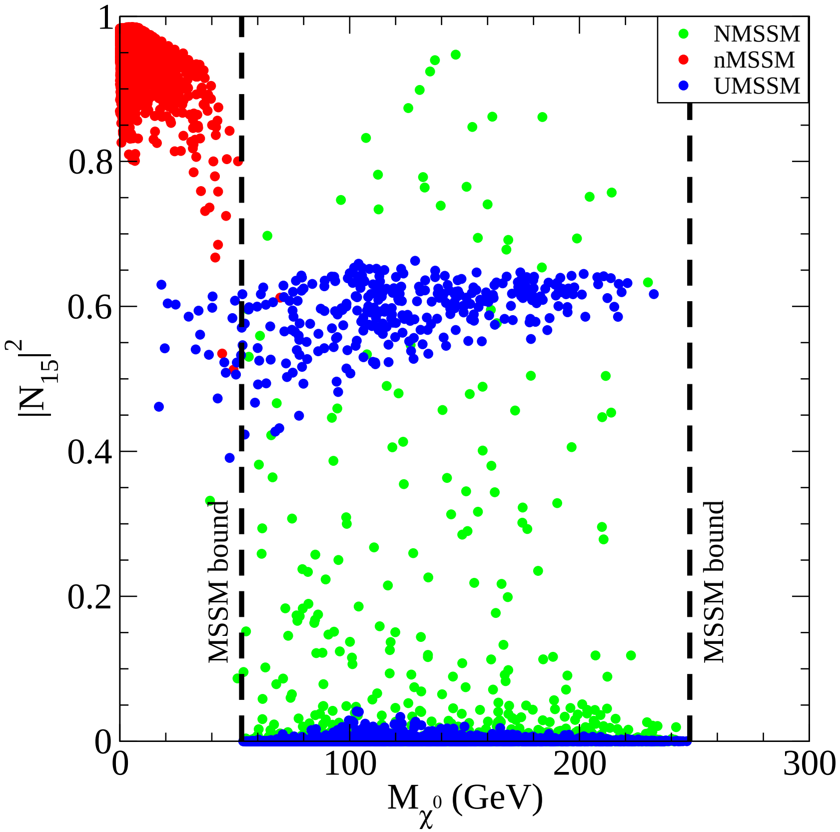
E_6 GUT (η-model) motivated couplings are used for UMSSM:

$$Q'_{H_1} = \frac{1}{2\sqrt{15}} \qquad Q'_{H_2} = \frac{4}{2\sqrt{15}} \qquad Q'_S = -\frac{5}{2\sqrt{15}} \qquad g_{Z'} = \sqrt{\frac{5}{3}} g_1$$

(i) Singlino dominance

Singlino ($\tilde{S}$) dominance in χ_1^0 is typical in extended-MSSM models.

Especially, $\tilde{S}$ dominates ($|N_{15}|^2 > |N_{1i\neq 5}|^2$) when $M_{\chi_1^0}$ is much smaller than the MSSM bound.



$|N_{15}|^2 = \tilde{S}$ composition of the χ_1^0

$$\left(\begin{array}{cccc} |N_{11}|^2 + & |N_{12}|^2 + & \cdots + & |N_{16}|^2 = 1 \\ \tilde{B} & \tilde{W}_3 & \cdots & \tilde{Z}' \end{array} \right)$$

(ii) Very light neutralino

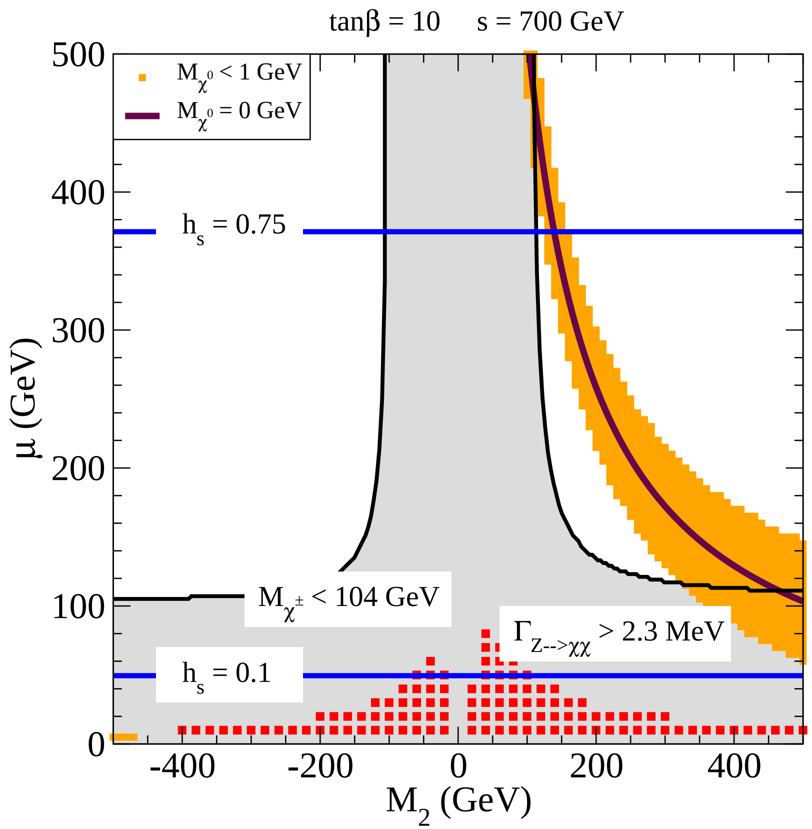
For example, in the nMSSM,

$\mathrm{Det}(M_{\chi^0}) = 0$ (massless state)

$$\to M_Z^2(M_1\cos^2\theta_W + M_2\sin^2\theta_W) = \mu M_1 M_2 \sin 2\beta$$

$$\to M_Z^2 \approx 0.8\mu M_2 \sin 2\beta$$

(with $M_1 \simeq 0.5 M_2$ condition)



Easy to satisfy this $\mathrm{Det}(M_{\chi^0}) = 0$ with μ and M_2 of $\mathcal{O}$(EW/TeV) resulting in massless χ_1^0 (and very light ones around).

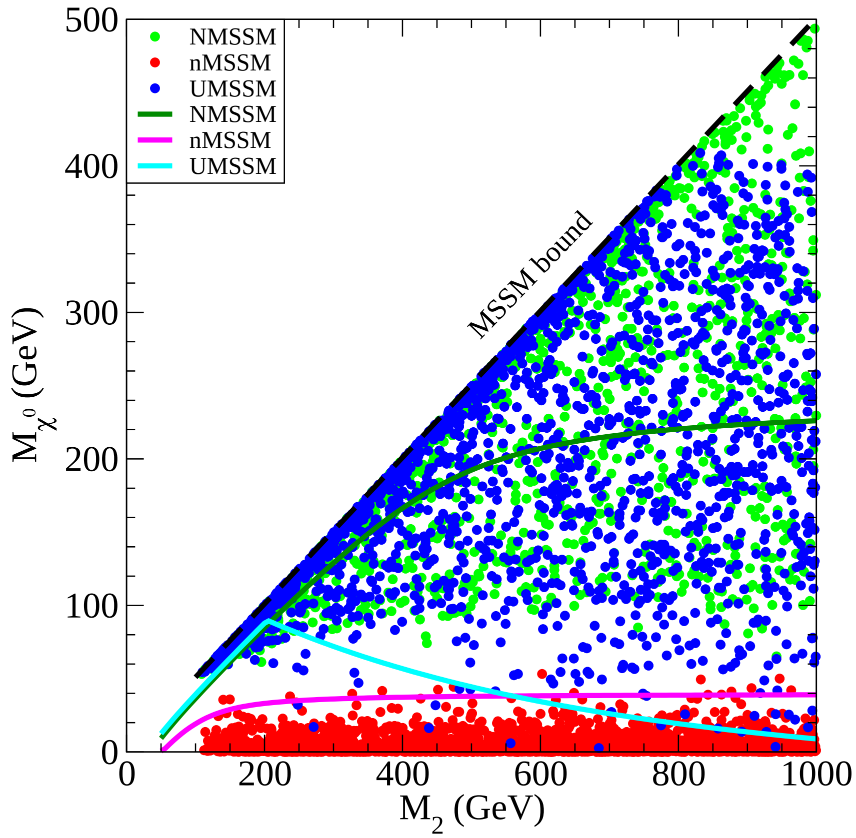
MSSM cannot have such a light χ_1^0 without fine-tuning.

(iii) Maximum $M_{\chi_1^0}$

$M_{\chi_1^0}^{\mathrm{Max}}$ increases with $M_1 (\simeq 0.5 M_2)$ for MSSM, NMSSM (and UMSSM before s bound is reached) with $\chi_1^0 \sim \tilde{B}$.

Maximum $M_{\chi_1^0}$ with $M_1 < 500$ GeV

Model	$M_{\chi_1^0}^{\mathrm{Max}}$	dom.	cutoff
MSSM	499 GeV	$\tilde{B}$	$M_1 < 500$
NMSSM	499 GeV	$\tilde{B}$	$M_1 < 500$
nMSSM	86 GeV	$\tilde{S}$	$h_s \leq 0.75$
UMSSM	421 GeV	$\tilde{B}$	$s < 2000$



(solid curves: $\mu = 250, s = 500, \tan\beta = 2, \kappa = 0.5$)

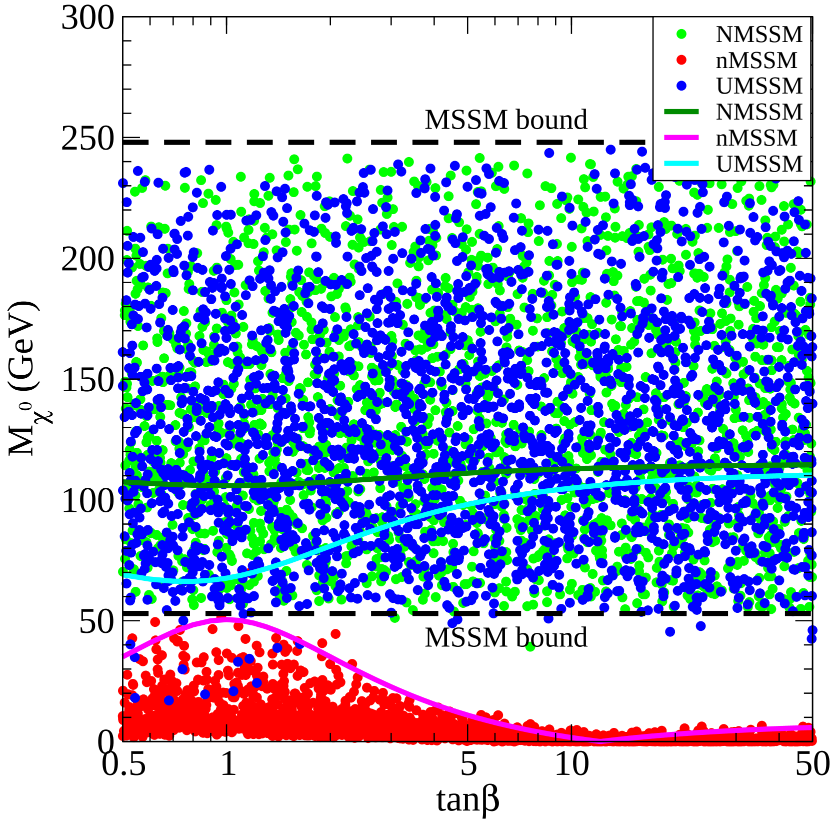
(iv) $\tan\beta (\equiv v_2/v_1)$ **dependence**

Each model shows different $\tan\beta$ dependence.

(ex) At $\tan\beta \simeq 1$.

- MSSM violates LEP m_{h^0} constraint.
- NMSSM dependence is small.
- nMSSM has Maximum $M_{\chi_1^0}$.
- UMSSM has minimum $M_{\chi_1^0}$.

(For sizable $M_{\chi_1^0}$ in the nMSSM, $\tan\beta$ should be small.)



(solid curves: $M_2 = \mu = 250$, $s = 500$, $\kappa = 0.5$)

Indirect constraints on the lightest neutralino (χ_1^0)

Additional Constraints

- nMSSM : Small lightest neutralino mass ($M_{\chi_1^0} = 0 \sim 83$ GeV)
  $\Omega_{\rm CDM} h^2 = 0.12 \pm 0.01$ (WMAP+SDSS CDM relic density)
  $a_\mu^{\rm exp} - a_\mu^{\rm SM} = (23.9 \pm 10.0) \times 10^{-10}$ (BNL $(g-2)_\mu$ deviation)

- UMSSM : Additional gauge boson of $M_{Z'} \sim \mathcal{O}$(EW/TeV)
  $M_{Z'} \gtrsim 600 \sim 800$ GeV (Tevatron bound on Z' mass)

CDM relic density

For very light χ_1^0, most MSSM annihilation channels are irrelevant.

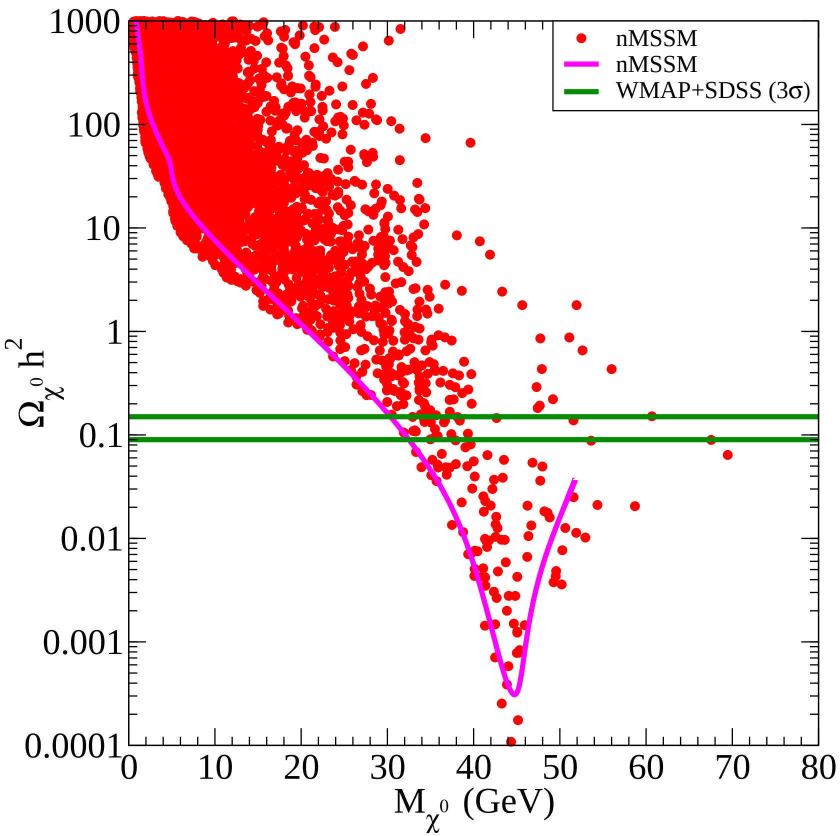
Z-pole is the most relevant channel in nMSSM and it constrains

$$M_{\chi_1^0} \gtrsim 30 \text{ GeV.}$$

Only small $\tan\beta$ is allowed.

[Menon, Morrissey, Wagner (2004)]

[Barger, Kao, Langacker, HL (2004)]



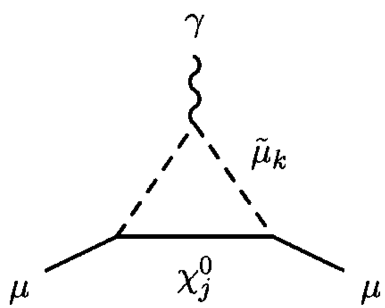
(solid curves: $\mu = 200, s = 400, \tan\beta = 1.5$)

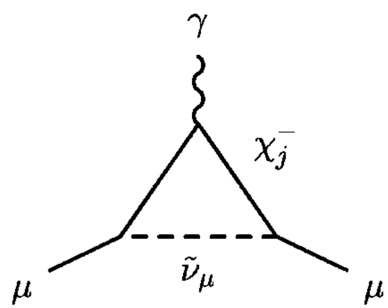
(Smaller $M_{\chi_1^0}$ may be allowed by $\Omega_{\text{CDM}}h^2$ with a very light Higgs.)

[Gunion, Hooper, Hess, McElrath (preliminary)]

Muon anomalous magnetic moment, $a_\mu \equiv \frac{1}{2}(g-2)_\mu$

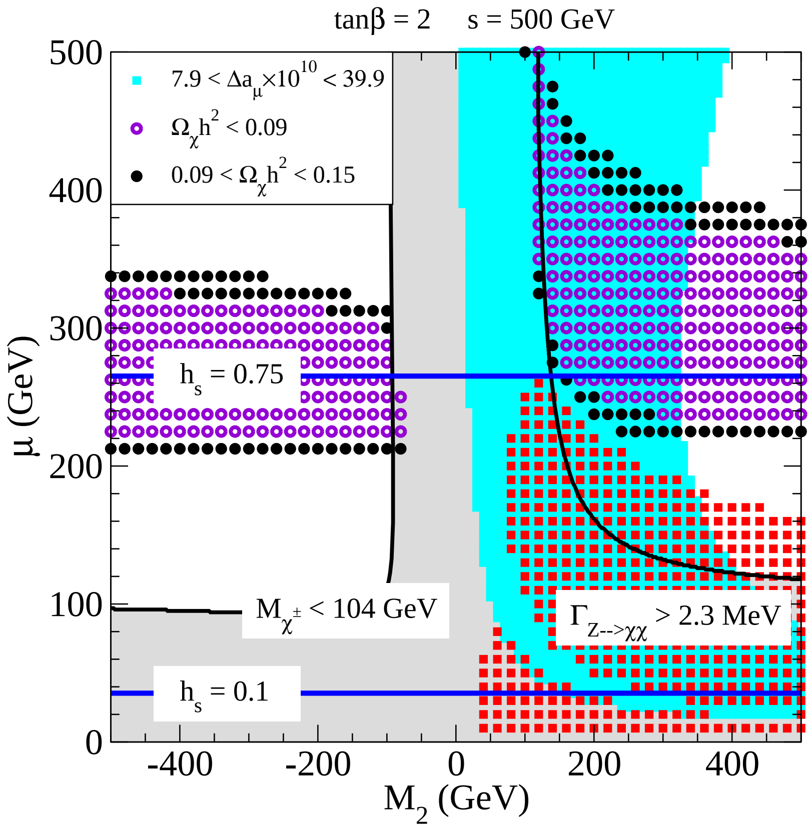
2.4σ deviation is well explained
by the χ^0, $\chi^\pm$ loop in the MSSM.
(only 0.9σ w/ indirect τ-decay data
instead of direct e^+e^- data)





Large $\tan\beta$ is preferred (while disfavored by relic density in nMSSM) :

$\Delta a_\mu \sim 13 \times 10^{-10} \frac{\tan\beta}{(M_{\rm SUSY}/100 \text{ GeV})^2}$ (for degenerate SUSY mass)



nMSSM with $m_{\tilde{\mu}_{\mathrm{L,R}}} = 100,\, A_\mu = 0$

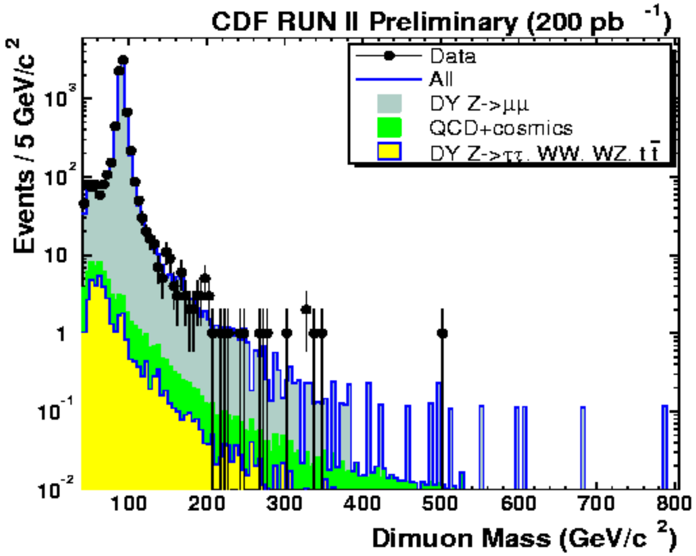
The Common solution of $(g-2)_\mu$ and relic density exists for nMSSM (despite the competition over $\tan\beta$). [Bager, Kao, Langacker, HL (2005)]

Z' mass bound

UMSSM predicts TeV-scale $U(1)'$ gauge boson.

$$M_{Z'} = g_{Z'} \left(Q'^2_{H_1} v_1^2 + Q'^2_{H_2} v_2^2 + Q'^2_S s^2\right)^{1/2}$$
$$\sim g_{Z'} |Q'_S| s \sim \mathcal{O}(\text{EW/TeV})$$

since $\mu_{\text{eff}} = h_s s/\sqrt{2} \sim \mathcal{O}(\text{EW/TeV})$

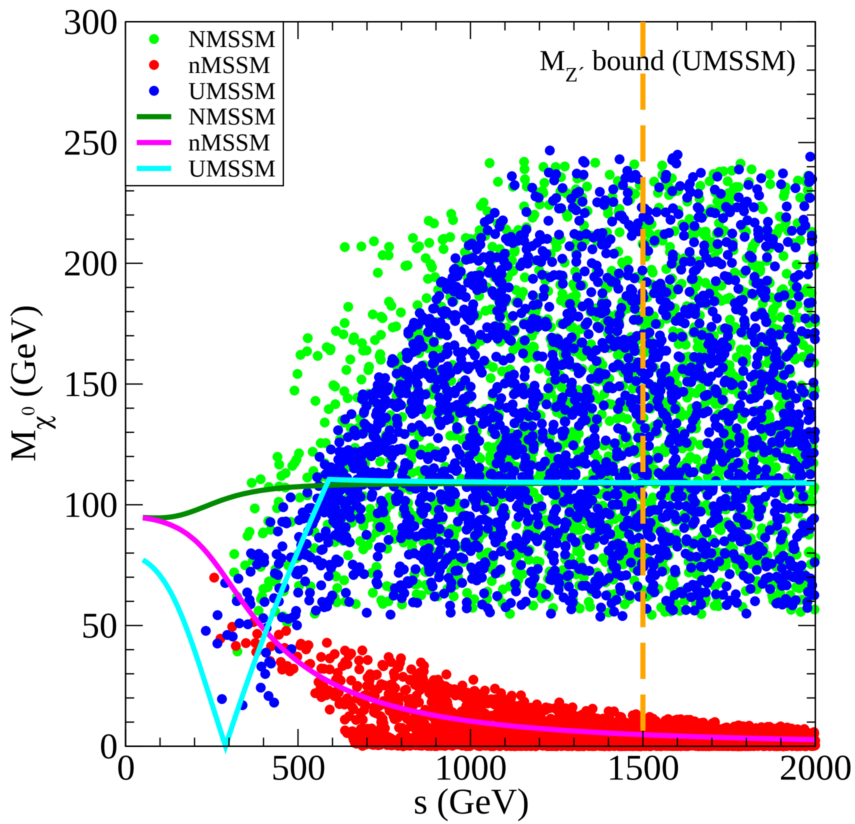


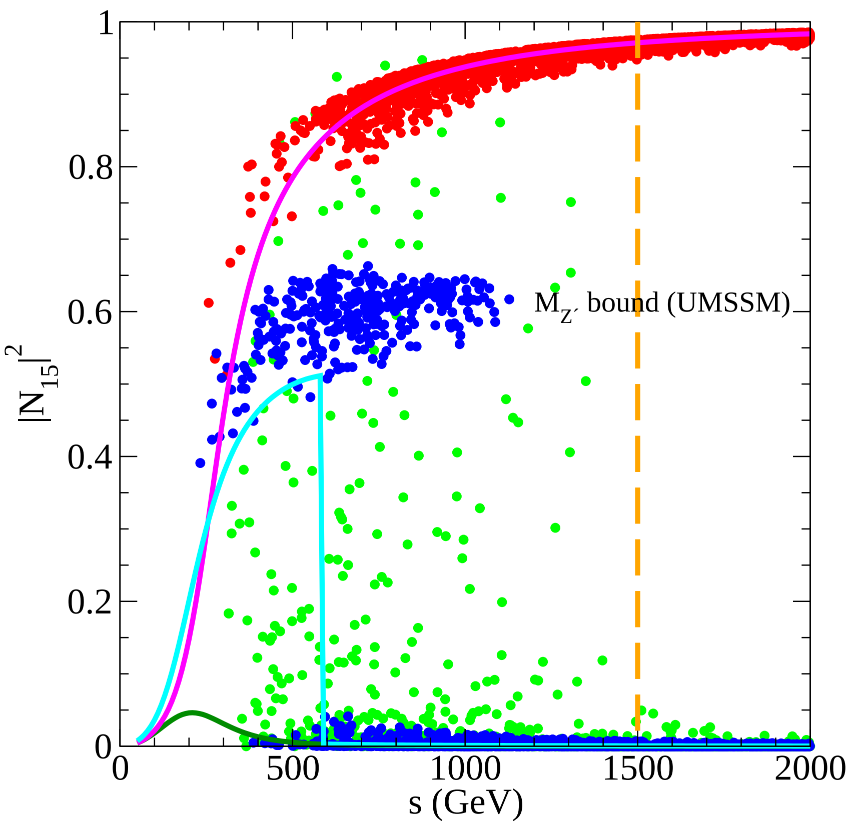
To satisfy $M_{Z'} \gtrsim 600 \sim 800$ GeV,

[see Karagoz Unel's talk for the most recent data]

UMSSM needs to have $s \gtrsim 1 \sim 3$ TeV.

Model	ee	$\mu\mu$	$\ell^+\ell^-$
Z'_{SM}	750	735	815
Z'_ψ	635	600	690
Z'_χ	620	585	670
Z'_η	655	640	715





(solid curves: $M_2 = \mu = 250, \tan\beta = 2, \kappa = 0.5$)

With $s > 1.5$ TeV condition, UMSSM χ_1^0 sheds its $\tilde{S}$ component.

$$50 \text{ GeV} \lesssim M_{\chi_1^0} \lesssim 250 \text{ GeV} \quad \text{[UMSSM]}$$

Ways to avoid $M_{Z'}$ constraint on s :

(i) additional contribution to $M_{Z'}$: e.g., $U(1)'$ model with multiple singlets (multi-S)

$$M_{Z'} = g_{Z'} \left(Q'^2_{H_1} v_1^2 + Q'^2_{H_2} v_2^2 + Q'^2_S s^2 + \sum_{i=1}^{3} Q'^2_{S_i} s_i^2 \right)^{1/2}$$

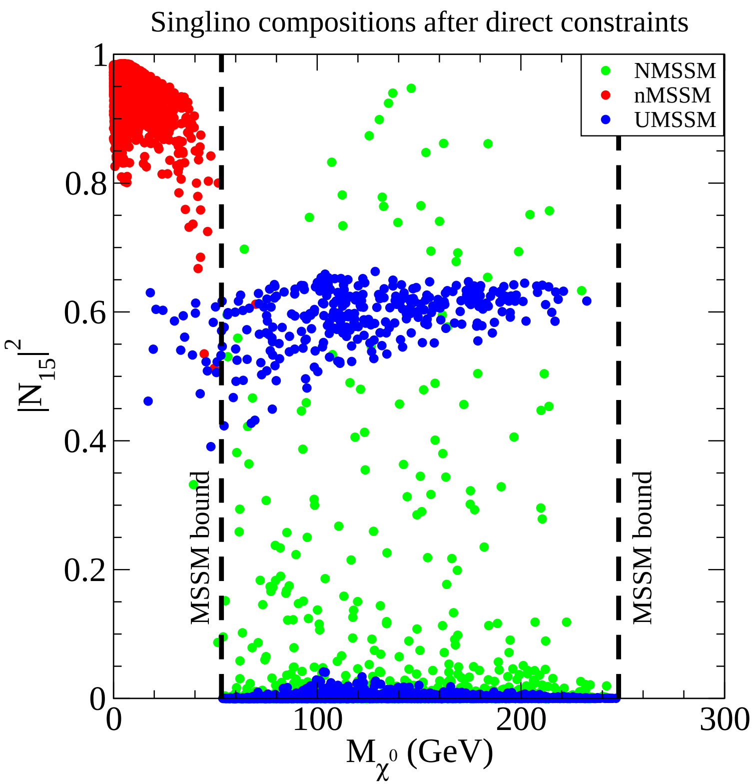
$$\mu_{\text{eff}} = h_s s / \sqrt{2}$$

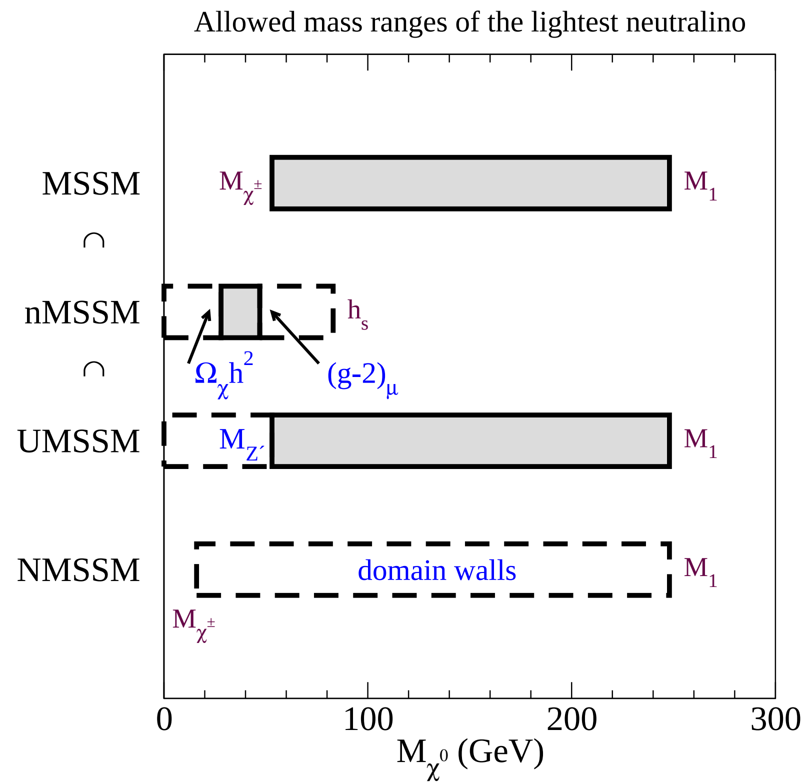
(ii) leptophobic Z' coupling : Z' coupling to leptons are significantly small

$\longrightarrow$ In these cases, there is no bound on s from Tevatron dilepton data.

Summary and Outlook

- We considered properties of χ_1^0 in various extended-MSSM models. (Indirect constraints might have way-arounds.)





- χ_1^0 (LSP, CDM) property may be very different from MSSM predition with additional components or interactions (e.g., χ_1^0 may be very light and/or dominated by singlino).

- Although TeV-scale SUSY is well-motivated, the MSSM is just one of its possible realizations.

- Other TeV-scale SUSY SMs (or extensions of MSSM) may have distinctive features (including neutralino and Higgs sectors). SUSY signals may look different depending on models.

- `SPIRES` search : "MSSM" hits ~ 1000, "NMSSM" hits ~ 50. Extended-MSSM models need more studies both in collider (e.g., trilepton signal by $\chi_1^{\pm}$-χ_2^0) and non-collider (e.g., CDM direct detection) physics.